THE SBRC-190
A CRYOGENIC MULTIPLEXER FOR MODERATE-BACKGROUND FIR ASTRONOMY

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ABSTRACT

The SBRC 190, a cryogenic multiplexer developed for far-infrared (FIR) photoconductor detectors operating at moderate backgrounds, is described. The circuit is based on the 32-channel CRC 696 CMOS device used on SIRTF. For applications such as encountered on SOFIA or Herschel, the new device permits higher backgrounds, a wider range of backgrounds, faster sampling, and enhanced synchronization of sampling with chopping. A relationship between sampling efficiency and noise requirements needed to achieve background-limited instrument (BLIP) performance is derived. Major design differences relative to the CRC 696 which have been incorporated in the SBRC 190 are: (a) an AC coupled, capacitive feedback transimpedance unit cell, to minimize input offset effects, thereby enabling low detector biases, (b) selectable feedback capacitors to enable operation over a wide range of backgrounds, and (c) clamp and sample & hold output circuits to improve sampling efficiency, which is a concern at the relatively high readout rates required. The paper emphasizes requirements for use on SOFIA, and touches on the design, expected performance, and fabrication of the new multiplexer.

INTRODUCTION

A monolithic, low noise, low power consumption, cryogenic multiplexer – the CRC 696 – was developed for far infrared germanium photoconductor detectors to be used in the low photon backgrounds expected on SIRTF (Young, 1994). The device features a DC-coupled CTIA (capacitive feedback transimpedance amplifier) unit cell, with 32-channel linear format multiplexer consisting of a decoder and transmission gate. The technology, developed at the (now defunct) Hughes Carlsbad Research Center, is a cryogenic CMOS process which allows both digital and analog low-noise elements on the same integrated circuit. Recognizing the need for a similar device suitable for the higher backgrounds anticipated on SOFIA (Erickson *et. al.*, 1996), we have developed the SBRC 190, a new integrated circuit based on the CRC 696 design, format, and technology.

The SBRC 190 unit cell is shown in Figure 1. Electronic considerations assumed detectors with ~ 1.5 pF capacitance. Some basic design requirements: Input debiasing at full well, offset uniformity, and node stability (1 hour): <1 mV; gain uniformity: <10%; format: 32 inputs, single output; mux addressing: 5 lines; readout: non-destructive; reset: global. Clamp and sample and hold circuits are included to increase sampling efficiency, which is important when chopping (see below). The chip is approximately 6x4x0.5 mm^3.

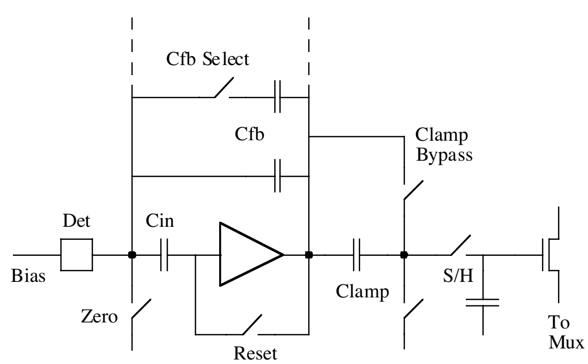

Figure 1. SBRC 190-2 unit cell.

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WELL CAPACITY AND NOISE

Our goal for the SBRC 190 is that its performance – read noise plus sampling efficiency – will allow the system sensitivity to approach the background-limited instrument performance (BLIP). The basic requirements to be determined are read noise, sampling efficiency, and well capacity, in addition to the electronic characteristics mentioned above. Of course the calculated system BLIP assumes some quantum efficiency, optical transmission, chopping efficiency, and background from the sky and telescope. To estimate the backgrounds, we consider two generic cases: high-resolution dispersive spectroscopy (case 1) and broadband imaging (case 2), and calculate examples at $\lambda = 100\ \mu m$. The photocurrent (electrons/second) is

$$i = \eta\ G\ F, \qquad (1)$$

where η is the quantum efficiency, G the photoconductive gain, and F the photon flux (photons per second) falling on the detector. A source with emissivity ε and temperature T produces a photon flux (photons/second) on a detector pixel of

$$F = \varepsilon\ \tau\ d\lambda\ [\ A\ \Omega\ B_\lambda(T)\ /\ h\nu\ ], \qquad (2)$$

where τ is the instrument optical transmission, $d\lambda$ is the bandpass, $A\Omega$ the throughput to a detector pixel, $B_\lambda(T)$ the blackbody brightness at wavelength λ. Background is produced by the sky, the telescope, and the cryostat window. On SOFIA these will have temperatures of roughly 220, 240, and 290 K, respectively; since we are making a rough estimate, we assume a single temperature of 240K.

The sky emissivity is a strong function of wavelength and bandpass, as well as observing conditions (Erickson, 1998); we assume a sky emissivity of 0.05 and 0.3 for cases 1 and 2, respectively. Emissivities of the telescope and window are assumed to be 15% and 5% for both cases. For τ we take 0.2 and 0.4 for cases 1 and 2. We assume a spectral resolving power of 1E4 for the case 1, and 25% for case 2, corresponding to $d\lambda = 0.01\ \mu m$ and $25\ \mu m$, respectively. Adding the emissivities gives a product $\varepsilon*\tau*d\lambda$ of 5E-4 for case 1, and 5 for case 2, so the photon fluxes in the two cases differ by roughly a factor of 1E4.

For throughput we use $A\Omega = 0.2\ \lambda^2$, which assumes a pixel size of $0.6\ \lambda/D$ (D = telescope diameter = 2.5 m); this is a pixel which Nyquist samples the diffraction spot of the telescope. At $\lambda = 100\ \mu m$, this pixel size is 5 arc seconds, and $A\Omega$ is 2E-5 cm^2 sr. The photon flux for a 1 μm bandpass, unit emissivity and transmission, $[A\ \Omega\ B_\lambda(T)\ /\ h\nu]$, is 1.5 E10 photons/sec, so that equation (2) gives F = 7E6 and 7E10 photons/sec for cases 1 and 2. For an ηG product of 0.2, equation (1) gives background photocurrents of 1.4E6 and 1.4E10 e/sec.

Photocurrents would be larger if a pixel is filled with a bright object (such as Mars), or smaller for a higher resolution spectrometer. Also, the value of ηG will depend on details of the detectors used: for example on the SIRTF MIPS unstressed Ge:Ga array ηG was estimated to be ~0.18*0.6 = 0.11. In addition, in a given instrument, backgrounds will vary as instrument parameters such as resolution or bandpass and wavelength are changed. However, as representative values, the photocurrents derived above are sufficient to specify the readout.

The readout rate is determined by the need to chop and the need to avoid over-filling the wells. Chopping is thought to be necessary on SOFIA to minimize "sky" noise. Generally the chop frequency is set to maximize sensitivity. The SOFIA chopper is designed to chop up to 20 Hz with a transition duration ~5msec. Slower chopping is more efficient, so frequencies below 20 Hz will certainly be used when possible, although expectations are that frequencies above a few Hz will be required. If f is the chopper frequency in Hz, then 500/f - 5 is the possible integration time in msec. Readouts and resets should be possible during the 5 msec chopper transition. With this information, we can specify minimum and maximum "Charge Cases" as shown in Table 1:

Table 1 Readout Perspective		
	Charge Cases	
Detector Parameters	minimum	maximum
F = photon flux per detector (photons/sec)	7E6	7E10
$g = \eta G$	0.1	0.4
i = background photocurrent = F*g (e/sec)	7E5	3E10
f = chopper frequency (Hz)	20	5
t = integration time = 500/f - 5 (msec)	20	95
n = background electrons during t = i*t (e)	1E4	3E9
N = shot noise in time t = $\sqrt{n}$ (e)	100	5E4
Related Basic Readout Features		
Desired read noise@: $N_r < N/2$ (e)	<50	<2E4
Desired well capacity: W > 1.3*n (e)	1.3E4	4E9

@ This read noise level will decrease the sensitivity relative to BLIP by about 10%.

A noise of ~50 electrons was achieved with the CRC 696 (Young, 1994). The SBRC 190 design features 8 feedback capacitors which are gang-selected with 3 digital lines, to provide the widest practical range of well capacities. The nominal values are 20, 46, 106, 243, 560, 1,287, 2,961, and 6,810 fF. FET gate capacitance is expected to increase the effective values of the smallest capacitors. At 1 Volt, the 8 capacitors span a range of well capacities W from ~1E5 to 4E7 electrons. Clearly the W value in the maximum charge case in Table 1 is out of reach; for such high currents, higher readout rates must be used.

READ NOISE AND SAMPLING EFFICIENCY

The lowest noise requirement corresponds to the minimum charge (worst) case, where Table 1 implies a read noise 50 of electrons. This is when minimum charge is accumulated before reading out, corresponding to the highest chopper rate and the lowest flux (case 1) and ηG. However, to evaluate the degradation of the system sensitivity caused by the readout, we must determine the combined effect of the mux read noise and the loss of possible integration time due to the mux sampling efficiency. Clocking while chopping requires attention to attaining the highest sampling efficiency.

We define the mux sampling efficiency, E (<1), to be the fraction of the duration of a chopper plateau which is spent accumulating signal. If the nominal plateau duration is t, then the effective integration time is E*t. There will be a relation between E and the mux read noise N_r to achieve a system sensitivity to within factor p of the BLIP; the smaller E is, the smaller will be the allowed read noise. Table 1 assumes E= 1. The data system will be adding up the contributions from many consecutive chopper cycles, for total integration times of up to an hour or more. Of course, the mux sampling efficiency for a single half chopper cycle will apply as well to the total integration time.

The device-dependent relationship between the sampling efficiency and the read noise will only be learned from experience. However we derive a relationship assuming they are independent. If I is the signal current and i the background current, then the measured signal-to-noise ratio will exceed the
BLIP SNR divided by a factor p (>1) if

$$E*t*I /(E*t*I + E*t*i + N_r^2)^{1/2} > t*I /p*(t*I + t*i)^{1/2} \quad (3)$$

The shot noise one would collect in time t is $N = (t*I + t*i)^{1/2}$. With some algebra (3) becomes

$$N_r < N * (E^2*p^2 - E)^{1/2} \quad (4)$$

Equation (4) encapsulates the combined requirement on read noise and sampling efficiency, and their dependence on the shot noise N generated in integration time t, assuming the read noise N_r is a constant. As an example, if we want the measured SNR to be within 40% of BLIP, then $p^2 = 2$; if $E = .75$, then equation (4) requires $N_r < 0.6*N$. Alternatively, one could of course restate equation (4) as an expression for p in terms of N_r, N, and E.

DEVELOPMENT

Four lots of wafers have been processed, but none had a good yield based on pass-fail criteria of warm foundry (parametric) and/or designer (probe) tests. However, some useable devices have been obtained, although they have parameters out of range and higher than nominal noise, based on preliminary testing (Farhoomand *et. al.*, 2002; Mason *et. al.*, 2002). If these fabrication problems can be resolved, the SBRC 190 should find a variety of important applications in far infrared astronomy.

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